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14. ABSTRACT
Flow separation limits the efficiency of low-pressure turbines (LPTs) in aircraft engines. Experiments with vortex generator jets (VGJs), conducted in AFRL"s low-speed cascade at Wright-Patterson AFB, have demonstrated dramatic reductions in separation losses. In an effort to enable the integration of flow control into LPT design, a combined experimental and computational study of pulsed vortex generator jets (VGJs) for flow control of turbine airfoils in realistic engine conditions was conducted. This work demonstrates integration of VGJ flow control into the design of aggressive turbine airfoils that augment available power beyond the limits of current performance. The performance of the new highly loaded L1A blade (designed by AFRL) was studied with and without VGJ flow control. Special effort was focused toward producing flow conditions similar to those experienced in application. Specifically, the impact of periodically impinging upstream wakes was examined. Studies were conducted to form recommendations regarding how best to simulate upstream vane wakes. Synchronization of pulsed VGJs with the passing wakes was also investigated in order to achieve optimal control with minimal mass flow. These efforts will aid in the integration of flow control into the blade

15. SUBJECT TERMS
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ABSTRACT

TITLE: DESIGN AND MODELING OF TURBINE AIRFOILS WITH ACTIVE FLOW CONTROL IN REALISTIC ENGINE CONDITIONS

PRINCIPAL INVESTIGATORS: Drs. Jeffrey P. Bons and Jen-Ping Chen, Ohio State University

PERIOD OF PERFORMANCE: Jan 2008 – Dec 2009 **OVERALL COST: ~$280,559**

A closely integrated experimental/numerical study of pulsed vortex generator jets (VGJs) for flow control of turbine airfoils in realistic engine conditions is proposed. This work will demonstrate integration of VGJ flow control into the design of turbine airfoils that go beyond the limits of current performance. The new L2M highly loaded blade designed by AFRL will be studied for performance both with and without VGJ flow control. Special effort is proposed to demonstrate performance in flow conditions similar to those experienced in application. Specifically, the effects of a full annulus vs. linear cascade will be examined, as will the effects of passing upstream wakes. Synchronization of pulsed VGJs with the passing wakes will be investigated in order to achieve optimal control with minimal mass flow. Implications for blade surface heat transfer will also be investigated. These efforts will aid in the integration of flow control into the blade design process, leading to innovative new designs and improved engine performance.

STATEMENT OF OBJECTIVES

TITLE: DESIGN AND MODELING OF TURBINE AIRFOILS WITH ACTIVE FLOW CONTROL IN REALISTIC ENGINE CONDITIONS

PRINCIPAL INVESTIGATORS: Drs. Jeffrey P. Bons and Jen-Ping Chen, Ohio State University

The specific objectives of the proposed research are:

- Use CFD to guide the design, construction, and validation of a linear cascade test section for the new L2M "ultra" highly loaded AFRL blade design.
- Explore the performance of the L2M over a wide range of Reynolds numbers (experimental and CFD at low Re, and CFD at high Re).
- Document the implementation of pulsed VGJs for flow control on the L2M design (CFD and Experiment).
- Document the effect of upstream wakes on the time-averaged and unsteady L2M performance (CFD and Experiment).
- Explore the synchronization of VGJs with unsteady wakes for optimal control authority at minimum massflow.
- Investigate the implications of VGJs/wakes for blade surface heat transfer.
- Aid the integration of flow control design tools into AFRL's blade design process in order to produce a "next-generation" turbine blade design.

TECHNICAL PROPOSAL

DESIGN AND MODELING OF TURBINE AIRFOILS WITH ACTIVE FLOW CONTROL IN REALISTIC ENGINE CONDITIONS

Drs. Jeffrey P. Bons and Jen-Ping Chen, Ohio State University

BACKGROUND/MOTIVATION

Overview: A number of studies, summarized by Rivir et al. [1], have shown considerable promise in the arena of low pressure turbine (LPT) separation control using embedded flow control devices. LPT separation is a loss-producing phenomenon that is primarily associated with low Reynolds number turbine operation [2-4]. For example, Sharma [3] reported a 300% increase in loss coefficient at Reynolds numbers below 95,000 for a research LP turbine, as illustrated in Fig. 1. Rivir et al. reviewed progress with a wide variety of flow control devices including passive surface protrusions (delta wings) and recesses (dimples), MEMs actuators, heated wires, electrostatic discharge devices, and vortex generating jets (VGJs). Of the active control devices listed, VGJs are perhaps the most straightforward to implement in an engine since the manufacturing technology required is virtually identical to that currently used for film cooling in high pressure turbine stages.

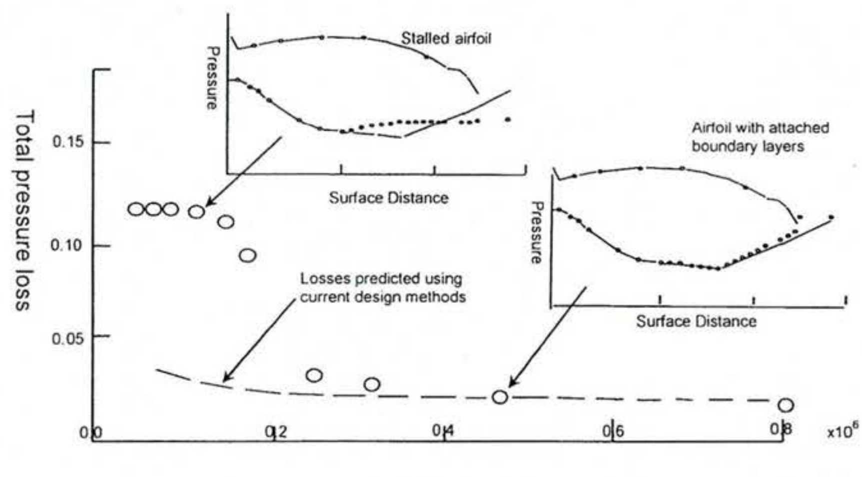


Figure 1: Increased Loss Coefficient due to separation at low Re (from Sharma [3]).

Steady VGJs with the Pack B: Experiments with vortex generator jets (VGJs), conducted in several low-speed turbine cascade facilities with the same Pack B LPT blade profile [5-8] have demonstrated substantial reductions in separation losses at low (separating) Reynolds numbers (25-65% depending on flow conditions). Figure 2 contains a sample of data acquired with two different linear cascade facilities using steady VGJs over a range of jet blowing ratios (B = jet velocity/local freestream velocity). VGJs are typically configured with a low pitch angle (30-45 degrees) and aggressive skew angle (45-90 degrees) to the near wall flow direction. Here pitch angle is defined as the angle the jet makes with the local surface and skew angle is defined as the angle of the projection of the jet on the surface relative to the local freestream direction (see inset in Fig. 2). When operated in the steady mode, it has been shown that the VGJ creates a vortex pair with one very strong leg accompanied by a weak leg of opposite sign [8,9]. The result is a single, dominant, slowly-decaying streamwise vortex that energizes the separating boundary layer by effectively bringing high momentum freestream fluid down near the wall. Figure 3 contains contour plots showing this vortical motion as measured using a 3-component PIV measurement technique, from Hansen and Bons

[9]. Experimental results have shown steady VGJs to be extremely robust with effective operation over a wide range of flow conditions (Reynolds number and freestream turbulence) and control implementations (chordwise location and blowing ratio) [2,5].

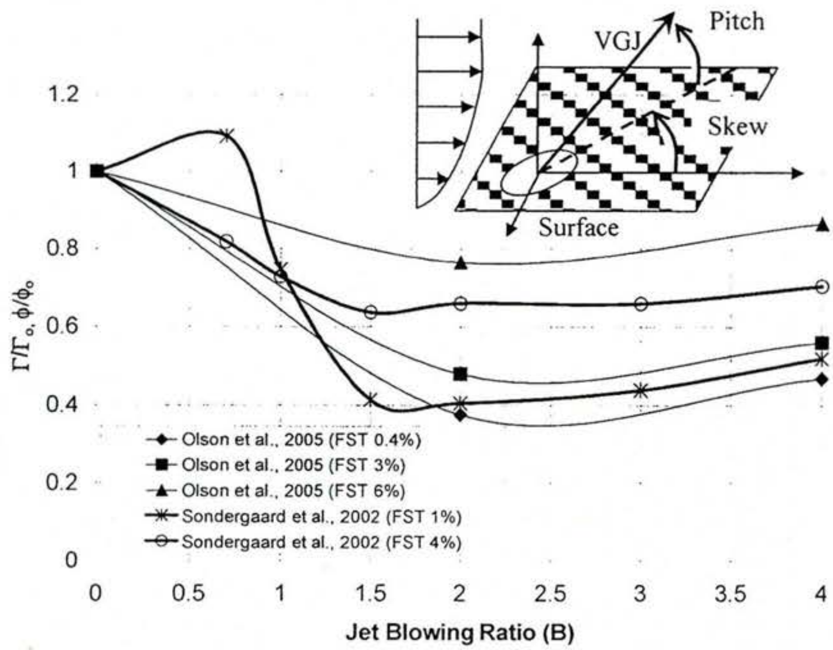
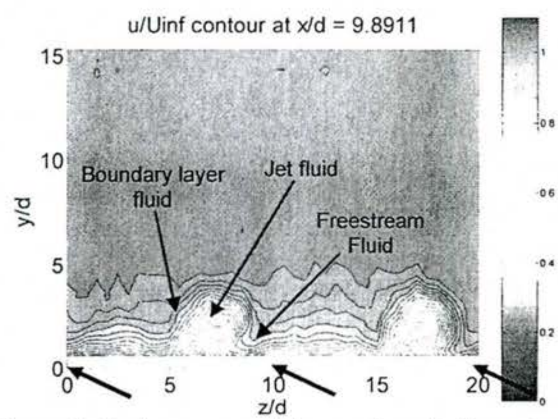


Figure 2: Reduction in blade loss coefficient with steady VGJ blowing (from Sondergaard et al., [2] and Olson et al. [10]). Data for Pack B airfoil with various freestream turbulence levels (FST). Re = 25,000.



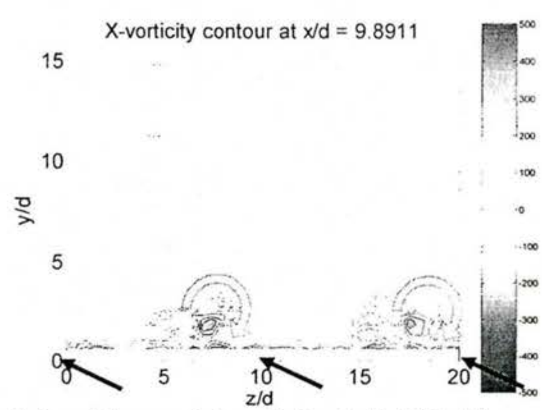


Figure 3: Contour maps of streamwise velocity and out of plane (streamwise) vorticity at x/d=10 looking downstream (d=jet diameter). Steady jet injection with B=2. Black arrows indicate jet injection points

Pulsed VGJs with the Pack B: Despite the success of steady VGJ flow control, the real promise for VGJ integration into a gas turbine engine is in the unsteady or pulsed mode. Laboratory tests indicate that the massflow requirements of VGJs can be reduced to an almost negligible fraction (<0.01%) of the core massflow through non-steady forcing [5]. And unlike flow control on external airfoils [11], pulsed VGJs implemented in an LPT cascade exhibit effectiveness for a wide range (3 orders of magnitude) of frequency. This finding bodes well for eventual VGJ integration in turbomachinery designs since embedded airfoils are already subject to a highly unsteady environment due to upstream wakes and secondary flows. It may be possible to synchronize VGJ actuation with the

rotor passing frequency such that the jet is phased to interact synergistically with the convected wake disturbance. To optimize the timing of pulsed flow control in this manner, the nature of the unsteady interaction of VGJs and the separated boundary layer must be better understood. Unlike in steady control mode, the flow mechanism responsible for pulsed VGJ separation control effectiveness is still unclear. An initial study by Bons et al. [5] varying the jet duty cycle from 50% to 1% suggested that the fluid dynamics associated with the initiation and termination of the pulse are the most critical. It was assumed that these transitions would be punctuated with vortical motions that would perform a comparable role to the streamwise vortices associated with steady VGJs (Fig. 3). However, computational studies by Postl et al. [12] showed that while pulsed VGJs generated some freestream entrainment through vortex interaction, the primary mechanism for boundary layer control is turbulent transition. They noted the presence of large amplitude 2D (spanwise) disturbances downstream of the VGJs that accelerated boundary layer transition, and thus reattachment. Subsequent work by Postl et al. [13] suggested that these 2D waves were more efficiently induced by normal jet blowing (vs. skewed injection). This finding was corroborated by experimental measurements of Hansen and Bons [9] which showed that normal and skewed pulsed jets have approximately the same effect on a separation bubble in a 2D diffusing flow.

<u>The New L1M Profile</u>: The forgoing studies have used the same "Pack B" research blade design from Pratt & Whitney, which is a Mach number scaled version of a modern highly loaded LPT blade design. As such, VGJs were being employed to correct a known low Reynolds number separation problem. In 2004, a re-design of the Pack B airfoil was performed using the airfoil design, analysis, and optimization system implemented recently at AFRL/PRTT [14]. The objective was to increase the blade loading above the Pack B level at constant axial chord and airfoil metal angles. VGJs were integrated into the initial design with the intent of actively suppressing any signs of flow separation. To that end, recently published transition models (Praisner and Clark [15]) and high-lift airfoil design information (Praisner et al. [16]) were used in conjunction with MISES and the flow solver of Dorney and Davis [17] to design an airfoil with a balanced loading distribution and 17% more lift than the original shape. The aft portion of the new blade profile is shown in Fig. 4 overlaid on the Pack B. The airfoil was predicted to have improved performance at low Reynolds numbers over the original blade, which was later verified experimentally in a linear cascade facility (Fig. 5). The new blade profile (termed "L1M" for Low pressure turbine 1st design Mid-loaded) was found to be resistant to un-reattached boundary-layer separation at inlet Reynolds numbers below 15,000. At the same time, significant separation bubbles were predicted to occur at inlet Reynolds numbers of 20,000 and 50,000, and it was shown experimentally that these separations were effectively controlled with pulsed-blowing from vortex generator jets (VGJs). The design and experimental validation of the L1M were presented at the 2005 IGTI [18].

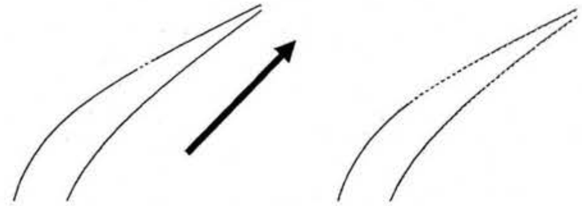


Figure 4: L1M blade design (red) overlaid on Pack B design (solid black). (Aft portion of cascade only.)

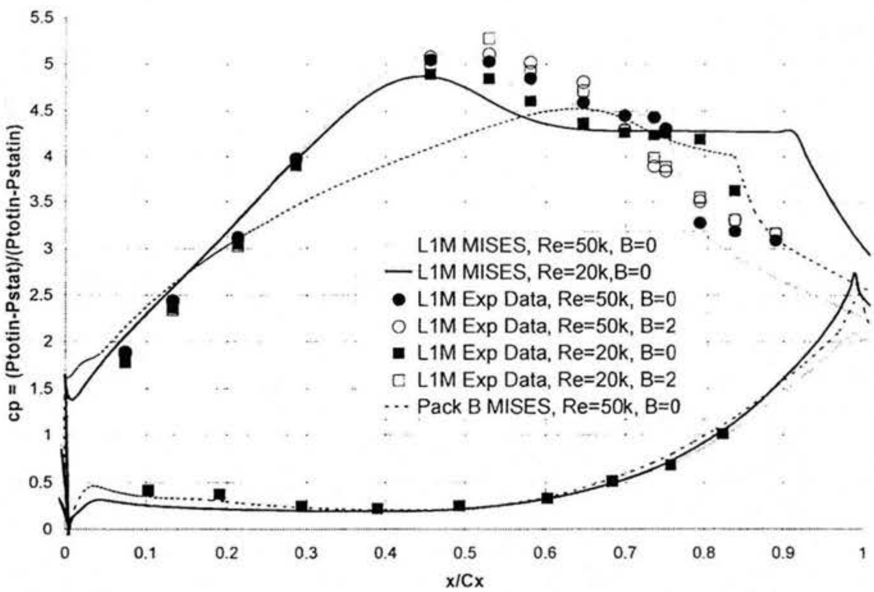
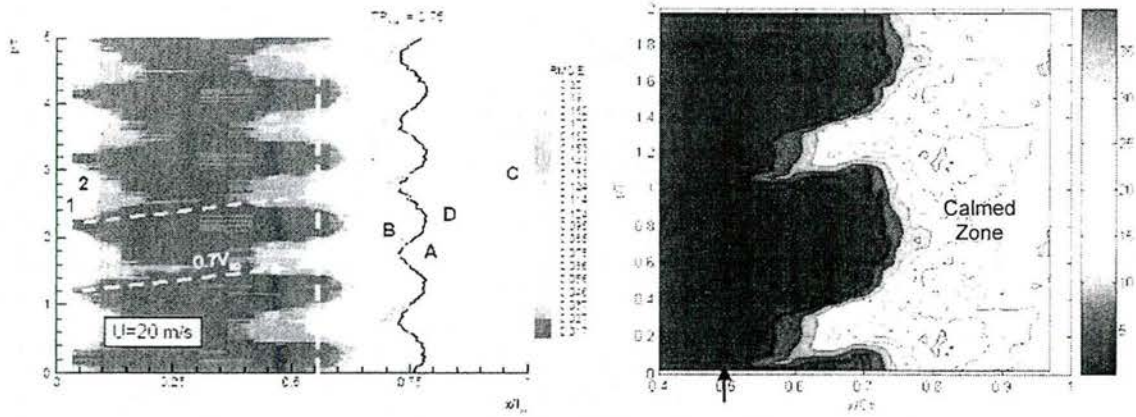


Figure 5: Experimental L1M c_p distribution for Re = 20,000 & 50,000 compared to MISES prediction. (Experimental data for B = 0 & 2) Pack B MISES calculation at Re = 50,000 shown for comparison.

Subsequent experimental work using pulsed VGJs with the L1M cascade at BYU showed limited evidence of streamwise vortex formation [19]. Rather, the jet unsteady forcing initiated a rapid reattachment at the leading edge of the separation bubble. Detailed time-resolved hot-film anemometry measurements provided evidence of a VGJ-initiated boundary layer transition emanating from the jet holes [20]. Thus, for the L1M profile, VGJs appear to act as discrete trips, causing reattachment of the separation bubble's upstream end. As this reattachment progresses, the bubble is pushed further downstream to the trailing edge in a 2D, spanwise-uniform fashion. Following control, separation reappears near the upstream extent of the preceding bubble and grows downstream to its full, uncontrolled extent. This physical development is distinctly different from the separation dynamics for a non-reattaching separation bubble [5], which was observed to reemerge from the blade trailing edge forward. An accurate understanding of the relaxation time associated with the reappearance of the separation could allow future designs to maximize control efficiency while minimizing the required jet massflow. It may also allow the designer to synchronize VGJ actuation with the rotor passing frequency such that the jet is phased to interact synergistically with the convected wake disturbance.

Several researchers have shown evidence of a "calmed zone" of well-attached laminar flow following the unsteady interaction of a wake disturbance with a separation bubble [21-23]. Figure 6(a), from Stadtmuller et al. [23], shows a time-space plot of surface heat flux data taken in a T106 LPT cascade with simulated upstream wakes. RMS fluctuations from the streamwise array of heat flux sensors over 5 wake periods show the influence of the convected wakes on boundary layer development. The dashed white line at $0.7V_\infty$ shows the trajectory of a convected wake and the elevated (red) RMS sawtooth pattern denotes the time-varying transition line. Of particular interest is the calmed region (letter B) just following the wake disturbance. Typically, this region of well-behaved flow persists for 20-40% of the wake passing period. For a separating LPT profile, this calmed region is followed by a gradual return to separated laminar flow prior to the arrival of the next wake disturbance [21]. Figure 6(b) contains a similar space-time plot of RMS velocity fluctuations taken with the L1M cascade using pulsed VGJs [20]. The jet is injected at x/Cx = 0.5 (note the black arrow) and the duty cycle is 25%. The injected jet wake initiates early transition (much like the wake disturbance) followed by a calmed zone (noted on the figure) of low turbulent fluctuations. One possible application of pulsed flow control would be to actuate near the end of the wake-induced calmed zone, thus preventing the return to a separated state. To optimize the timing of pulsed flow control in this manner, the nature of the unsteady interaction of VGJs and the separated boundary layer must be better understood.



(a) rms heat flux measurement vs. wake passing (from [22]) **(b) u_{rms}/U_{in} vs. VGJ pulsing period (from [19])**

Figure 6: Time history plots of (a) rms surface heat flux with convected wake disturbances and (b) rms velocity fluctuations for pulsed discrete VGJs.

<u>Specific Air Force Need</u>: Test results to date suggest that the integration of active flow control into LPT blading could revolutionize blade design. Ultra-aggressive blade profiles could be used that are inherently unstable, relying on flow control to insure efficient flow turning. With broad engine integration, VGJ flow control blading could be used to (1) obtain the same blade loading with reduced axial chord, (2) increase blade loading at constant chord and solidity, or (3) decrease solidity at constant blade loading. As such, the liberal use of VGJs in blade design could potentially pave the way to savings in engine weight and/or part count without a loss in stage efficiency. Thus, engine thrust/weight could be increased allowing longer range missions and/or larger operational payloads. Alternatively, excess power produced by the LPT could be used to operate energy-consuming onboard surveillance, targeting, and laser-defense systems. In addition, reduced part count would decrease operating and maintenance costs over the life-cycle of the engine.

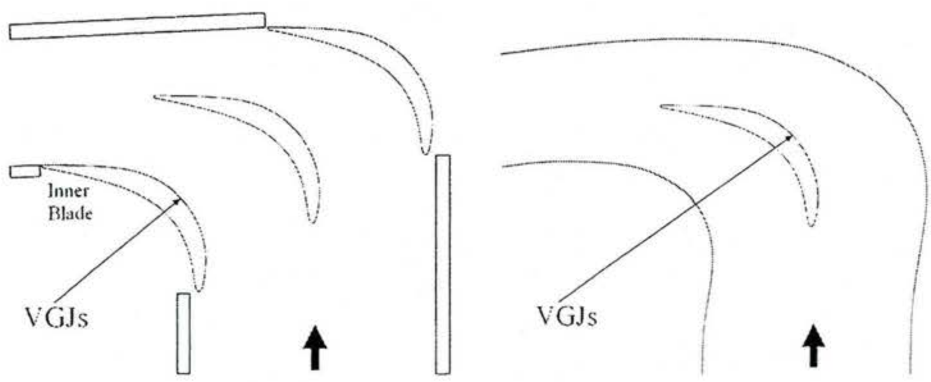
OBJECTIVES:

The primary objective of this proposed research is to demonstrate, both experimentally and computationally, the integration of VGJ flow control into the design of turbine airfoils that go beyond the limits of current performance. To increase the relevance of this study to the engine design community, this study will include the influence of several "realistic" engine effects, such as: unsteady wakes, full annulus vs. linear cascade, high Reynolds numbers, freestream turbulence, and surface heat transfer. Collaboration with AFRL/PRTT's turbine research/design team (Drs. John Clark, Rolf Sondergaard, Richard Rivir, and Peter Koch) will continue as new blade designs are developed and tested (e.g. L2M, L3M, etc...). A better understanding of the role of VGJ-induced boundary layer transition will allow the development of accurate flow control models that could eventually be integrated into AFRL's turbine design system. Finally, this research effort will be conducted as a truly integrated experimental/computational study, with both approaches integrated together as closely-coupled tools to understand this complex flow control application. Geographic proximity of the two principal investigators will facilitate this close cooperation. It is hoped that this will provide a template for future joint experimental/computational studies of similarly complex physical phenomena.

STATEMENT OF WORK:

These objectives will be accomplished through the following series of tasks:

1) AFRL/PRTT is currently designing a 2nd generation blade profile ("L2M") using the same methodology employed for the L1M but with a much higher loading objective. The goal is to design a blade that is completely dependent on successful flow control to insure its performance over all Reynolds number regimes (not just at low Re). Dr. John Clark has agreed to make the L2M profile available for this proposed research effort. Once this new profile is received from AFRL, we will perform two-dimensional flow simulations of the L2M in a finite-blade linear cascade similar to OSU's current L1M cascade facility [Fig. 7(a)]. These CFD results will be used to guide the design and construction of a new L2M experimental test section for OSU's turbine cascade facility. Rather than rely on coarse adjustments to the straight wall sections used in the current cascade for tailboards and inlet bleeds [Fig 7(a)], the shape of the L2M cascade sidewalls will be contoured based on the CFD calculations. These continuous tunnel surfaces will be optimized to insure that the flow around the central blade resembles (as closely as possible) the flow in an "infinite" cascade (i.e. full annulus). Specifically, the surface pressure distribution computed for the fully periodic case will be used as a target for an inverse design of the contoured cascade walls. Laskowski et al. [24] recently demonstrated this integrated design process for a single-blade transonic high-pressure turbine cascade with remarkable success.



(a) Current L1M Cascade Design **(b) Conceptual L2M Cascade Design**

Figure 7: (a) Current linear cascade facility for L1M and Pack B research. (b) Conceptual L2M cascade section with CFD-aided design of contoured endwalls and inlet bleeds (blue lines).

2) Once constructed, the linear cascade will be evaluated experimentally at low Reynolds numbers ($\leq$100,000) and computationally at higher Reynolds numbers (up to 500,000) without flow control. The two databases will be compared at select overlapping Re values. Comparisons will also be made with AFRL/PRTT's own analytical predictions, as was done previously with the L1M [20]. All studies will be conducted with the 3-4% background level of freestream turbulence that is typical of embedded blade rows.
3) The application of pulsed VGJs to the L2M will be evaluated experimentally and computationally at multiple Reynolds numbers. The TURBO code [25], an in-house 3D finite-volume compressible Navier-Stokes code will be employed for this study. Boundary and inlet conditions will be continuously updated and shared between the two parallel studies. Due to the first-order effect that flow control will have on the blade circulation, it is expected that the tunnel walls will need to be modified/adjusted to simulate a full annulus of controlled blades. CFD will again be employed to guide this design modification. The combined results of experiment and CFD will be evaluated to answer the following fundamental questions:
    a. What is the role of boundary layer transition in pulsed VGJ control?
    b. What produces the rapid evolution from discrete jet disturbances to the spanwise structures seen in previous studies?
    c. What is the minimum jet spacing needed to produce the spanwise (2D) flow control?
    d. What are the physics that dictate the phase lag observed between the termination of forcing and re-separation of the flow?

The answers to these questions should indicate whether it is possible to develop a model of the discrete VGJ forcing that could be incorporated into a 2D design code (e.g. with AFRL).

4) An upstream wake-generator will be designed, constructed, and installed in the linear cascade facility. Figure 8 shows a wake-generator concept currently being explored for incorporation with the linear cascade facility shown in Fig. 7. Preliminary results with a prototype of this mechanical configuration have been encouraging. In private discussions with AFRL/PRTT, Dr. Rolf Sondergaard has suggested that the standard moving cylindrical bars used in previous wake studies [21,22] inadequately represent the wake from an upstream blade row in terms of shed vorticity and range of turbulent scales. Accordingly, CFD will again be employed to determine a more accurate moving wake-generator. A preliminary study with a candidate "slotted" cylindrical wake-generator has been performed, showing considerable promise. Figure 9 compares large-eddy simulation calculations of wakes from both a closed and slotted circular cylinder in crossflow. The slotted arrangement successfully breaks up the large scale vortex street typical of low Reynolds number flow over a bluff body. Other designs, including non-circular wake generators, are currently being explored as well.

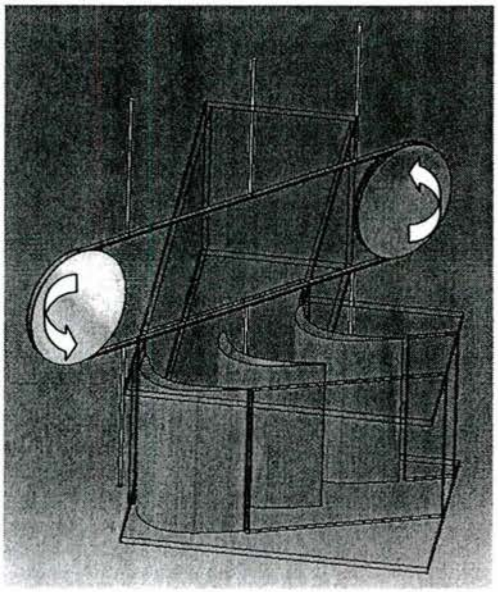


Figure 8: Conceptual design of wake generator with current (L1M) linear cascade facility.

(a) Standard closed cylinder **(b) "Slotted" cylinder**

Figure 9: Instantaneous iso-vorticity surfaces from CFD calculation of cylinder wake for (a) standard closed cylinder (b) "slotted" cylinder. $Re_D = 5,000$.

5) The unsteady, wake-affected, turbine flowfield will be studied both with and without pulsed flow control. This will be done both experimentally and computationally, with the CFD simulations focused on the higher Re cases which are beyond the capabilities of the linear cascade facility and mechanical wake-generator. The phasing and duty cycle of the forcing will be varied to answer the following questions:

a. What role do wake-induced calmed zones play on the L2M?
b. What is the optimal phasing for the application of control?
c. What is the minimum massflow requirement for adequate control?

6) In addition, at least one of the unsteady VGJ/wake cases will be run computationally with the full experimental test section modeled with the results being compared to those obtained with a single blade and periodic boundary conditions (i.e. an infinite blade row). This will help to identify any differences between the flow control results in a finite cascade and expected performance in a full engine annulus.
7) Surface heat transfer will be measured experimentally on the L2M blade with VGJs and wakes to assess the heat transfer implications of flow control. Though LPTs are currently uncooled, current initiatives to shorten combustors and reduce turbine stages may require internal cooling for more of the turbine components. Measurements of the surface heat transfer with and without flow control will allow an assessment of any potentially harmful aspects of flow control. We have made arrangements to collaborate with Dr. Richard Anthony (AFRL/PRTT) to benefit from his expertise in thin film heat flux gages.
8) It is expected that the above results will provide substantial guidance for the development of future turbine blade designs. A constant, open dialogue with AFRL/PRTT during this effort will allow further iterations on the L2M design, hopefully generating improved designs for multiple applications (e.g. L3M, etc...). Updated designs will be incorporated into the proposed test sequence as guided by AFRL/PRTT. Collaboration will also continue with comparison of results from PRTT's own cascade facilities.

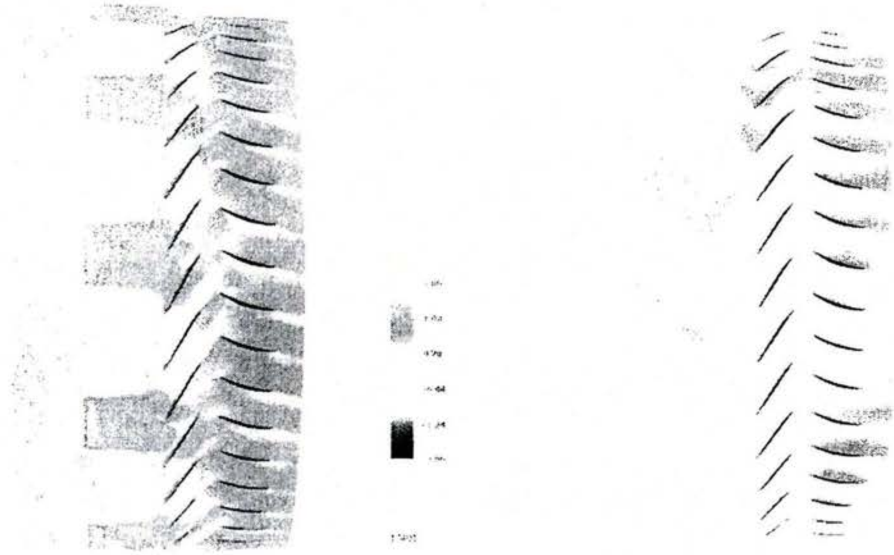
TOOLS:

These objectives will be accomplished by integrating the following experimental and computational tools over a suitable range of parameters indicated above:

- Planar 3 component velocity surveys using 3D PIV. Measurements will be both phase-locked and time-averaged.
- Localized time-resolved 1 and 2-component velocity measurements using hot-wire anemometry to determine turbulence statistics and identify the role of boundary layer transition.
- Surface pressure measurements
- Surface heat flux gages (in collaboration with AFRL/PRTT)
- Fluent, a commercial 2D or 3D pressure-based finite-volume code containing a wide variety of steady/unsteady formulations and various turbulence models, including dynamic large-eddy simulations.
- It is planned to use the turbomachinery CFD code TURBO to conduct the CFD portion of the plan. TURBO is a simulation tool for multistage turbomachinery. This code solves the unsteady 3-D Navier-Stokes equations with a suite of turbulence models that are capable of RANS modeling and Detached Eddy Simulation (DES). This code is capable of computing the unsteady interactions of flow control devices: for example, the unsteady upstream wake effect on the downstream turbine blades.

A film cooling model using the body-force approach, where the fluxes of mass, momentum, and energy are specified for the film cooling jet, has been used to simulate various flow control techniques. One example is the simulation of a transonic compressor stage with endwall injection [26]. The TURBO prediction of the steady injection using a full-annulus grid is shown in Figure 10, in which the axial velocity contours near the casing with and without injection are shown. This operating point is very close to the stall margin of the compressor that if without the tip injection, will develop into the unstable stall condition. In Figure 10(b), reverse flows indicated by the negative axial velocity (shaded green) identify the stall cells in the early formation of the rotating stall. The injected flow, seen as the high axial velocity ahead of the rotor in Figure 10(a), was shown to effectively remove the stall cells. The results showed that a decrease in mass flow over the no-injection base flow condition can be obtained, thus increase the operating range of the compressor. This range extension is same as that found in the NASA experiments.

We plan to extend this flow control capability to model the pulsed vortex generator jets and to examine their effects on the turbulence transition of the boundary layer.



(a) with injection **(b) without injection**

Figure 10. Axial velocity of Stage 35 at early stage of stall formation